# Cooperative Distributed Problem Solving for Controlling Semi-Autonomous and Autonomous Oceanographic Sampling Networks

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## LONG-TERM GOALS

This report covers the final portion of the second phase of a long-term collaborative project between the Department of Computer Science, University of Maine, and The Autonomous Undersea Systems Institute (AUSI). This program is focused on developing an intelligent control mechanism for an autonomous oceanographic sampling networks (AOSN). An AOSN [4] is defined as a group of underwater vehicles and instrument platforms (VIPs) that can autonomously or semi-autonomously work together to carry out long-term sampling missions in an area of interest.

The long-term goal is to develop an AOSN control mechanism that can autonomously or semi-autonomously control an AOSN as it conducts long-term, complex missions. A part of this goal is to develop a language that can be used among the VIPs as they accomplish a defined task within the AOSN. This AOSN control scheme will allow the components of an AOSN to be deployed, then have them autonomously self-organize into an AOSN that can effectively carry out a mission. Related work, also funded by ONR (grant number N0001-14-98-1-0648), focuses on assigning mission tasks to VIPs within the AOSN and on selecting an appropriate organizational structure (e.g., a hierarchy) to use to conduct the mission given a specific mission, environment, and AOSN composition (i.e., which vehicles and instrument platforms are present and functional).

## OBJECTIVES

The major objectives of this program are to: (1) develop a set of high-level cooperative problem-solving protocols for the organization and reorganization of a group of vehicles and instrument platforms (VIPs) that are the components of an AOSN; (2) develop a language that will allow VIPs to communicate as required to implement multi VIP cooperation; (3) design and implement simulation tools to model the aggregate behavior

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of an AOSN conducting a mission in accordance with the protocols; (4) develop and conduct experiments on those simulation tools to show the feasibility of this approach; and (5) make the results of this work readily accessible by the AUV development community.

**APPROACH**

In a truly autonomous AOSN, or even a semi-autonomous AOSN that that is only loosely controlled by a user, there can be no single vehicle or instrument platform (VIP) that has complete control. A vehicle or instrument platform, being a real physical system, is subject to failure. Should a controlling VIP fail, the AOSN would become non-functional. A pre-defined hierarchy of controllers and replacement controllers could be set up, but this is both overly restrictive (depending on the environment and mission, some VIPs may be better situated to perform control tasks than others) and still depends on VIPs being present that may have failed. A better approach is to provide the AOSN's VIPs with the ability to cooperatively decide how to control the AOSN, and to ensure that this mechanism does not depend on the presence of any particular VIP or small set of VIPs.

An approach has been developed to AOSN control called CoDA (Cooperative Distributed AOSN control) in which the AOSN is treated as a *multiagent system* (MAS). All VIPs can be thought of as being described by their set of capabilities (elsewhere called *generic behaviors* [3]). Some VIPs have sufficient intelligence that one of their capabilities is the ability to make AOSN control decisions. In the CoDA approach, these VIPs organize themselves into a relatively loose, unstructured *meta-level organization* (MLO). Part of this task involves each of the ``intelligent'' VIPs getting some idea of which of their peers, if any, are present. Since the only assumption made about the composition of the AOSN at this point is that there is at least one of these agents present, the MLO can almost always be formed. The MLO then acts as a group decision-making entity to discover the capabilities of the AOSN as a whole, analyze the mission and environment in light of the AOSN's capabilities, and then design an appropriate organization for the AOSN's agents to carry out the mission.

This second organization is called the *task-level organization* (TLO). An example TLO might be a hierarchy, possibly with multiple levels, with some agents managing others. The agents that are part of the MLO usually assume roles in this organization, as well. The TLO is designed to fit the particular situation, and so it is more efficient (in terms of problem-solving effort, communication, etc.) but not as flexible as the MLO. It gets control from the MLO and then carries out the mission.
If there is a change in the mission, the environment, or the composition of the AOSN itself (e.g., an agent fails or a new agent with useful capabilities enters the system), then the TLO will try to accommodate itself to the change. It can do this by reassigning agents, making use of slack resources, and so forth. However, since it is designed for efficiency, not flexibility, many changes will be beyond its ability to adapt. When this occurs, a new MLO will form, which will then either modify the TLO or design a new organization to fit the changed situation. A new MLO is needed because during the time the TLO was working, one or more of the old MLO agents may have left or new agents capable of participating in the MLO may have arrived.

Problem-solving protocols, which can be thought of as rules of cooperative behavior, have been created for each phase of the operation of each organization. In addition, protocols have been developed for exceptional circumstances, such as VIPs leaving the system or failing and VIPs entering the system. Each VIP has a set of protocols that it must follow to participate in the AOSN. More capable agents (i.e., those that can participate in MLOs) have different protocols than less capable agents. In this way, each agent knows how to behave to create and/or participate in the MLO and TLO, while no single agent has permanent sole responsibility for critical parts of AOSN control. In a way, the AOSN emerges from the interaction of its parts as they follow the protocols.

A task-assignment mechanism has also been developed to assign mission tasks to the most appropriate VIPs, based on their capabilities and resources. The MLO uses this once an organizational structure for the TLO has been created to assign roles within the TLO to VIPs. This mechanism is based on the idea of *constrained heuristic search* (CHS) [5]. A mission is represented as a task decomposition tree (TDT), which is an AND-OR graph of possible ways to carry out the mission. (Techniques, such as automated planning, exist to create such trees.) The task assignment mechanism creates a constraint graph from the TDT that represents the capabilities needed, the capabilities available aboard VIPs, and constraints between the VIPs undertaking various roles (e.g., resource constraints that limit how many roles of a particular kind the VIP can simultaneously perform). To create the constraint graph, the mechanism uses properties of the TDT to predict properties of the graph; this lets it make intelligent decisions about which branches to include in the final solution to help ensure a solvable constraint graph, and one that can be solved in a reasonable amount of time. The resulting constraint graph is then solved to provide a unique assignment of VIPs to worker roles in the TLO, and another mechanism adds management roles and fills them. In future work, we will look at merging these two parts into one CHS-based mechanism.

An organization-selection mechanism is also needed by the MLO to allow it to select an appropriate organizational structure for the TLO. This problem is being addressed in a related project. The organization selected is the source of the management roles in the TLO; in the current work, the structure is always a multilevel hierarchy.

AUSI is working in the lower level realm of determining the Generic Behaviors (GBs) of various kinds of submersible VIPs, VIP to VIP communications of same, and simple mission environment simulation. The GB approach is geared to identify the agent capabilities that result from behaviors that are generic to the diverse systems that will be found in a functioning AOSN. Since agents will communicate with each other about their capabilities, a language for expressing those GBs is being defined. As an aid to working in this area, AUSI has developed the Cooperative AUV Development Concept (CADCON) simulation facility. This is a distributed multi-agent simulation and visualization control harness designed to simulate a fairly accurate underwater environment which can be shared by simulated or real VIPs connected via the Internet.

## WORK COMPLETED

This report describes Phase II of the program. During Phase II, researchers at UMaine continued and extended the work begun in phase I of this project. In phase I, protocols were developed for most of the phases of AOSN operation, and work on a task-assignment mechanism was begun. This mechanism extends others' work on constrained heuristic search (CHS) to handle the special needs of problem-solving systems such as AOSNs. A simulator, based on the CLIPS rule-based language, was constructed to simulate the aggregate properties of a group of VIPs following the protocols. The simulator was designed to be a multi-fidelity simulator, in that it would ultimately be able to simulate an AOSN at different levels of detail. During the first phase, it operated in a low-fidelity mode.

Protocols now cover the remaining phases of AOSN control except the TLO work phase. The TLO work phase protocols depend on the kind of organization being used. During the past year (summer, 1999), an undergraduate student researcher was funded[1] to work on this problem for one kind of organizational structure, a multi-level hierarchy. She was able to add the ability to simulate simple sampling missions to our CoDA simulator. Work continued during this past year on the task-assignment mechanism, partly funded by the companion ONR grant.

The task-assignment mechanism was improved during this past year. Another undergraduate student researcher changed how constraints are represented in the task-assignment program. Now, instead of constraints being represented as explicit lists of possible values of the constrained variables (as is usual in constraint-based reasoning work), they are represented functionally. The result is a much faster and less space-intensive program. In addition, work began on comparing our CHS-based mechanism to another constraint-based mechanism that is seeing increased use in the domain of job shop scheduling [1]. Work continues on this as the student's senior project.

The CoDA simulator was enhanced during this year to facilitate its ability to support experiments. A graduate student and the first undergraduate student researcher worked on improving the experiment harness for the simulator. This involved adding an interface to the UMass CLIP program to our simulator to allow data collection and automated experiment performance. This work was done during the summer of 1999 and is now essentially complete. At the time of writing, experiments are underway to characterize the performance of CoDA in terms of message passing, time to organize/reorganize, and so forth.

Also during this past year, a third undergraduate student researcher worked on a project that will ultimately enable higher-fidelity simulation of aspects of CoDA. He implemented an interface between our Orca autonomous underwater vehicle (AUV) [6] mission planner and the Naval Postgraduate School's Underwater Virtual World (UVW) simulator [2]. This is a first step toward making Orca available to control realistic simulated AUVs of the sort that will participate in AOSNs. The student's work will be directly applicable to our future efforts to have instances of Orca follow CoDA protocols as they control AUVs in AUSI's CADCON multi-agent simulator [3].

Work also continued, funded in part by the companion grant, to identify those features of the situation, mission, and AOSN that are important to selecting a TLO organizational structure.

At AUSI, researchers focused on expanding the investigations into the Generic Behaviors (GBs) required to implement cooperation among real VIPs. This work centered on developing the structure of the GBs and developing a tool that allows evaluation of the developed GBs. The; CADCON (Cooperative AUV Development Concept) tool, consists of a server and five clients being developed to evaluate the cooperation of multiple, simulated AUVs moving about in a shared undersea environment.

**RESULTS**

At UMaine, an enhanced set of protocols to control AOSN agents; an improved task assignment mechanism; enhancements to the CoDA simulator to facilitate conducting experiments; and an interface between a mission planner and a high-fidelity simulator that will support future simulation and testing of the CoDA protocols have

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[1]Funds for students during the past year came not only from this grant, but from the companion ONR grant. We view this work as contributing to both projects, and so it is reported here.

been completed. Meaningful experiments to validate the usefulness of the CoDA approach to AOSN control can now be undertaken during the next phase of the project, high-fidelity simulation and testing.

At AUSI, researchers are now able to evaluate the use of Generic Behaviors as a language to implement cooperation between VIPs. The CADCON tool allows simulation of the communication between multiple VIPs of varying functional capabilities as they accomplish simple tasks.

## IMPACT/APPLICATIONS

This work is applicable to a wide range of distributed systems, including AOSNs involved in oceanographic or intelligence gathering missions, cooperative mine-clearing systems, and others of interest to the Navy. The mechanisms being developed here will have applicability to any such system that needs to autonomously self-organize and reorganize as the situation changes. The work also has wider applicability to other distributed systems and should be of interest to other researchers in multi-agent systems and distributed artificial intelligence. The evolving CADCON tool provides a communication infrastructure that will allow researchers to easily evaluate initial, high-level control strategies for multi-AUV cooperation. It is hoped that the GB concept will provide a starting point in developing a standard language for cooperation among VIPs

## TRANSITIONS

Versions of the CoDA simulator and documentation of the protocols are made available via the World Wide Web as they are ready for distribution. The Generic Behaviors (lowest level behaviors) are being evaluated by a number of organizations as part of their efforts in ONR VSW/SZ program. CADCON has been used to support the development of a magnetic navigation system. Its AUVSIM client was modified to represent a bottom crawling vehicle and then used to evaluate specific algorithms to be used in the ONR funded development program.

## RELATED PROJECTS

A related effort focusing on the selection of organizational structures for the TLO is also funded by ONR (N0001-14-98-1-0648). This involves analyzing the features of the situation and using that analysis to select an appropriate organizational structure for the situation. This project has ties to work in case-based reasoning, context-sensitive reasoning, and organizational theory.

The Orca project [6] is also related to this project, as it will provide the intelligent AUV controller for inclusion in our simulated AOSNs.

Another project, funded by the National Science Foundation (IRI-9696055), looks at when cooperating agents should send information to one another. This will be of great benefit during the TLO phase of AOSN control and possibly during the MLO phase as well. Heuristics and techniques developed in that project can likely be incorporated into future versions of the MLO and TLO protocols to enhance the behavior of the AOSN control mechanism with respect to both bandwidth utilization and speed of decision making.

Another project funded by ONR (N00014-97-1-0155) is investigating the use of solar energy as the energy source for an AUV. The goal of this project is to make available AUVs with an endurance of weeks to months. VIPs with such extended endurance could well be one of the cornerstones to the AOSN concept. This project is also utilizing the CADCON tool and is currently developing the ASMAC (Autonomous Systems Monitoring and Control) client to be used for controlling groups of VIPs.

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